

# Two Sun-like Superflare Stars Rotating as Slow as the Sun\*

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## Abstract

We report on the results of high dispersion spectroscopy of two ‘superflare stars’, KIC 9766237, and KIC 9944137 with Subaru/HDS. Superflare stars are G-type main sequence stars, but show gigantic flares compared to the Sun, which have been recently discovered in the data obtained with the Kepler spacecraft. Though most of these stars are thought to have a rotation period shorter than 10 days on the basis of photometric variabilities, the two targets of the present paper are estimated to have a rotation period of 21.8 d, and 25.3 d. Our spectroscopic results clarified that these stars have stellar parameters similar to those of the Sun in terms of the effective temperature, surface gravity, and metallicity. The projected rotational velocities derived by us are consistent with the photometric rotation period, indicating a fairly high inclination angle. The average strength of the magnetic field on the surface of these stars are estimated to be 1-20 G, by using the absorption line of Ca II 8542. We could not detect any hint of binarity in our spectra, although more data are needed to firmly rule out the presence of an unseen low-mass companion. These results claim that the spectroscopic properties of these superflare stars are very close to those of the Sun, and support the hypothesis that the Sun might cause a superflare.

**Key words:** stars:abundances stars:activity stars:flare stars:individual(KIC 9766237, KIC 9944137) stars:rotation

## 1. Introduction

A flare event on the Sun was visually noticed, and recorded by Carrington (1859) for the first time. Since then, many solar flares have been observed in all the wavelengths, and these are now generally explained by explosive release of the magnetic energy stored around sunspots (for a review, e.g. Shibata & Magara 2011). The total energy released in the largest solar flares was estimated to be of the order of  $10^{32}$  erg (e.g. Priest 1981; Emslie et al. 2012), while a possibility has been recently discussed that the most energetic solar flares caused extreme cosmic-ray events evidenced by isotopic abundance research of historical relics (Miyake et al. 2012; Usoskin & Kovaltsov 2012; Melott & Thomas 2012; Miyake et al. 2013). Such strong solar flares could have a severe effect on the terrestrial environment.

Many ‘superflares’ were discovered in G-type main sequence stars, namely solar-type stars, in 2012, and 2013 (Maehara et al. 2012; Shibayama et al. 2013), while only nine such events had been reported before it (Schaefer, King & Deliyannis 2000).<sup>1</sup> Superflares are eruptive events having an energy 10 to  $10^6$  times larger than that of the largest solar flare recorded so far. Such events have been found in many T Tau stars, RS CVn-type binaries, and dMe stars (e.g. Shibata & Yokoyama 2002). Before the advent of high-precision space photometry, however, it had been difficult to detect a superflare in white light in solar-type stars, due to contrast reasons. Indeed, even the largest solar flares could increase the total luminosity of the Sun by only 0.03% even at the peak of the event (e.g. Kopp, Lawrence & Rottman 2005). This situation has been recently changed by the Kepler spacecraft which observed a sky region between Cygnus and Lyra, monitoring over 160 thousand stars with a cadence of about 30 minutes, and a quite high accuracy exceeding 0.01% for moderately bright stars (Koch et al. 2010). Kepler data have been then used for the stellar flare research on cool stars (e.g. Walkowicz et al. 2011), and on hot stars (Balona 2012). We hereafter call those solar-type stars showing superflares ‘superflare stars’.

The analyses of the Kepler data by Maehara et al. (2012) and Shibayama et al. (2013) revealed that the relation between the occurrence frequency of the flare and the flare energy in the Sun can be roughly extended for the flare energy up to  $\sim 10^{36}$  erg on superflare stars. Shibayama et al. (2013) also estimated that a superflare with an energy of  $10^{34-35}$  erg occurs once in 800-5,000 years in Sun-like stars, i.e. main-sequence stars with the effective temperature in the range 5600–6000 K, and the rotational period longer than 10 days (see also Shibata et al. 2013). This rotation period is, however, estimated from the brightness modulation, assuming that it is due to the rotation of the star, whose photosphere is covered by large starspots (see

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<sup>1</sup> Some of these nine flares seem doubtful. Gmb 1830 (=HR 4550) have a flare star companion, CF UMa (see Reid 1991). The superflare visually observed on S For is suggested to be due to mis-identification (see Payne-Gaposchkin 1952; Ashbrook 1959). In addition,  $\kappa$  Cet and  $\pi^1$  UMa rotate with a period of 9.24 d, and 4.89 d, respectively, and are rather young (age < 1 Gy) (Linsky et al. 2012).

Notsu et al. 2013b). The rotation period then should be spectroscopically confirmed. In addition, the stellar parameters, and binarity of the superflare stars should be checked for the discussion whether the Sun can really give rise to superflares, or not.

We have then performed high-dispersion spectroscopy of superflare stars in our database. In this Letter, we report on the first results of the analysis of high-resolution spectra of two G-type stars, namely KIC 9766237 and KIC 9944137, whose rotation period was estimated to be 21.8, and 25.3 days, respectively (Shibayama et al. 2013). Figure 1 shows an example of the Kepler light curve of these targets, around the only one flare of each star automatically detected by the method described by Maehara et al. (2012). Quasi-periodic modulations with an amplitude of  $\sim 0.1\%$ , other than the superflare, are clearly present. The total energy released during the superflares marked in figure 1 is estimated to be  $\sim 10^{34}$  erg, and the duration is 0.1-0.2 days. Table 1 summarizes the effective temperature, surface gravity, and metallicity of KIC 9766237, and KIC 9944137, listed in the Kepler Input Catalog (Brown et al. 2011). Table 1 also lists the data of 18 Sco, the best investigated solar twin (e.g. Porto de Mello & da Silva 1997; Soubiran & Triaud 2004), for comparison.

The details of our observation of the targets are summarized in section 2. Section 3 describes the observational results, and brief discussion.

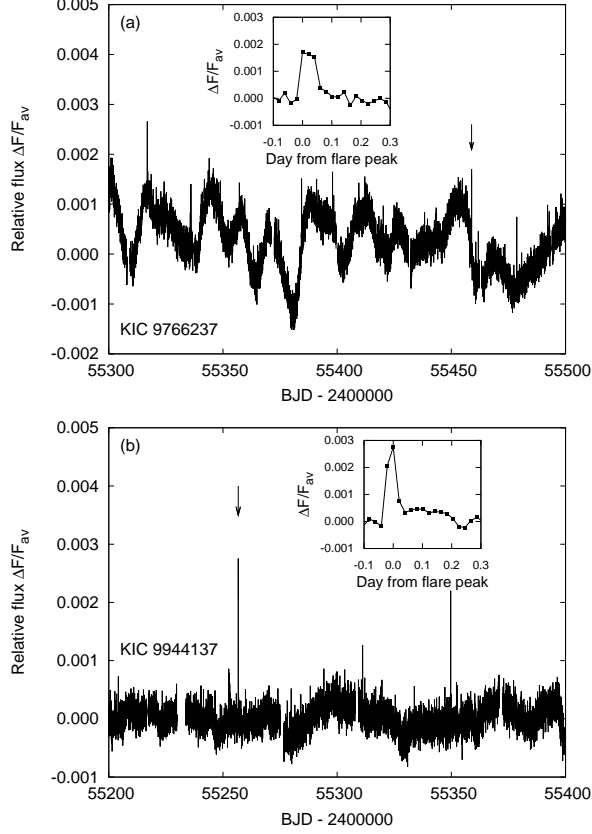
## 2. Observations

The observation of KIC 9944137, and 18 Sco was carried out on 2013 June 23, with the High Dispersion Spectrograph (HDS; Noguchi et al. 2002) attached to the 8.2-m Subaru telescope. KIC 9766237 was observed with the same instrument on 2013 June 24. The total exposure time for KIC 9766237, KIC 9944137, and 18 Sco was 4800 sec ( $1200 \text{ sec} \times 4$  sequential images), 4200 sec ( $1400 \text{ sec} \times 3$  sequential images), and 20 sec ( $10 \text{ sec} \times 2$  sequential images), respectively. The spectral resolution was  $R \sim 80,000$ . The wavelength coverage was 6,100-8,820 Å, which includes the chromospheric-activity sensitive lines of  $H\alpha$ , and Ca II IR triplet 8498, 8542, 8662. The  $2 \times 2$  on-chip binning mode was adopted. We used the image slicer #2 (Tajitsu, Aoki, & Yamamuro 2012). We reduced the Echelle-image data to 1-dimensional spectra in the standard way with IRAF.<sup>2</sup> The signal-to-noise ratio (S/N) is  $S/N=60 \sim 70$  around Ca II 8542 for KIC 9766237, KIC 9944137, and  $S/N > 200$  for 18 Sco.

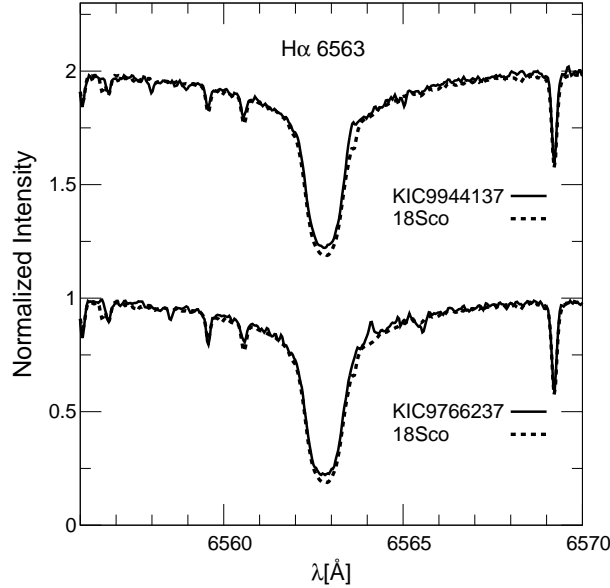
The radial velocity of KIC 9766237, KIC 9944137, and 18 Sco was estimated (see next Section) to be  $-56.1(\pm 0.3)$ ,  $-31.8(\pm 0.3)$ , and  $11.9(\pm 0.3) \text{ km s}^{-1}$ , respectively, by using the photospheric absorption lines. Per each star, all the sequential spectra were combined into a single co-added spectrum, and the correction for the radial velocities was performed before the following analyses.

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<sup>2</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.



**Fig. 1.** (a) Typical light curve of KIC 9766237 drawn with the long cadence Kepler data. The Y axis represents the relative flux normalized by the average flux  $((F - F_{av})/F_{av})$ . Quasi-periodic modulations with a timescale of about twenty days are seen. A tick mark points out the superflare automatically detected by the method described in Maehara et al. (2012) and Shibayama et al. (2013). The inset figure shows an enlarged light curve around the ticked superflare. The amplitude is about 0.17 %, and the duration is about 0.1 days. Though many ‘spikes’ other than that superflare are seen, all of them consist of only one point, and are not judged as a superflare with our criteria. (b) The same as (a), but of KIC 9944137. The amplitude of the superflare in the inset figure is about 0.28 %, and the duration exceeds 0.2 days.



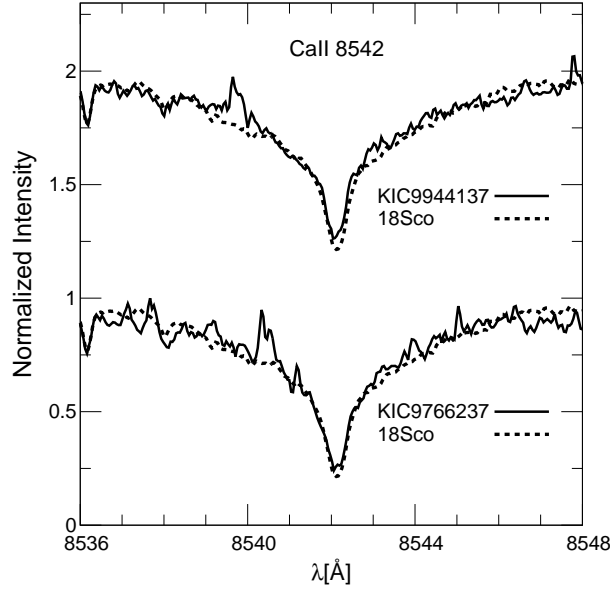
**Fig. 2.**  $H\alpha$  absorption line of KIC 9766237, and KIC 9944137 (solid lines), and 18 Sco (dashed lines). The  $H\alpha$  depth of these targets is slightly smaller than that of the comparison solar-twin star, 18 Sco. The spectrum of KIC 9944137 accompanying that of 18 Sco is shifted by +1.0 along the Y axis, for clarity.

### 3. Results and Discussion

Figures 2, and 3 show absorption lines of  $H\alpha$ , and Ca II 8542. They are good indicators of the chromospheric activity (e.g. Frasca et al. 2010; Takeda et al. 2010). Both lines of both targets are slightly shallower than those of the solar twin star, 18 Sco, that has the same activity level of the quiet Sun on the basis of the Mt Wilson Ca II S index (e.g. Duncan et al. 1991). The index  $r_0(8542)$ , the flux normalized by the continuum level at the line core of Ca II 8542 is 0.26 for KIC 9766237, 0.27 for KIC 9944137, and 0.21 for 18 Sco. These index values and effective temperature of  $T_{\text{eff}} = 5606\text{K}$  for KIC 9766237, and  $T_{\text{eff}} = 5666\text{K}$  for KIC 9944137 (derived later) suggest that both targets are in the region dominated by quiescent dwarf stars in figure 6 in Notsu et al. (2013a), though the shallowness of  $H\alpha$  and Ca II, compared with those of 18 Sco, indicates a little higher atmospheric activity level of both stars.

The average magnetic field can be roughly estimated, by using the emission core flux of Ca II. The relation between the emission core flux of the Ca II K line and the average magnetic field was first derived for cool stars by Schrijver et al. (1989). Notsu et al. (2014, in preparation) have extended this relation to the emission core flux of the Ca II 8542 and the average magnetic field. The average strength of the magnetic field of KIC 9766237, and KIC 9944137 is estimated to be 1-20 Gauss, by using this method. This value is of the same order as, or one order of magnitude higher than that of the Sun ( $\sim 2$  G).

An example of the photospheric absorption lines is displayed in figure 4. The profile of these photospheric lines are in good agreement with that of 18 Sco. This fact suggests that



**Fig. 3.** Absorption profile of Ca II 8542, one of Ca II IR triplet, of KIC 9766237, and KIC 9944137 (solid lines), and 18 Sco (dashed lines). This line of both targets is slightly shallower than that of the comparison solar-twin star, 18 Sco. The spectrum of KIC 9944137 accompanying that of 18 Sco is shifted by +1.0 along the Y axis, for clarity.

**Table 1.** Stellar parameters of KIC 9766237, KIC 9944137, and 18 Sco

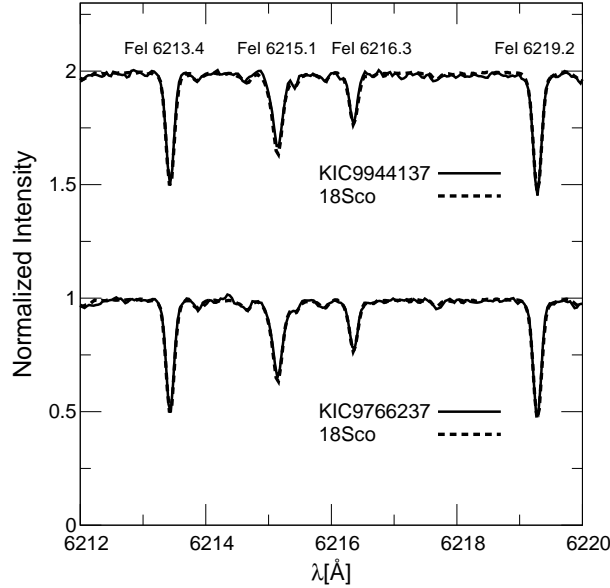
Name	Sp. Type	$T_{\text{eff}}$ [K]	$\log g$ [cgs]	[Fe/H]	$v \sin i$ [km s <sup>-1</sup> ]	A(Li)	Reference <sup>†</sup>
KIC 9766237		5674	4.557	-0.147			KIC
		5606(±40)	4.25(±0.11)	-0.16(±0.04)	2.1(±0.3)	<1.0	this study
KIC 9944137		5725	4.619	-0.064			KIC
		5666(±35)	4.46(±0.09)	-0.10(±0.03)	1.9(±0.3)	<1.0	this study
18 Sco	G2V	5816	4.45	0.04	2.1	1.63	1,2,3
		5824(±15)	4.50(±0.04)	0.07(±0.02)	2.4(±0.3)	1.6(±0.2)	this study

<sup>†</sup>1: da Silva et al. (2012), 2: Petit et al. (2008), 3: Meléndez & Ramírez (2007)

both of KIC 9766237, and KIC 9944137 are single stars, or at most single-lined binaries.

An analysis of the co-added spectrum of KIC 9744237, KIC 9944137, and 18 Sco yields the stellar parameters of the effective temperature  $T_{\text{eff}}$ , surface gravity  $\log g$ , projected rotational velocity  $v \sin i$ , metallicity [Fe/H], and lithium abundance A(Li) (table 1). The details of this analysis method were described by Notsu et al. (2013a).

While the values of  $T_{\text{eff}}$ ,  $\log g$ , and [Fe/H] we derived are rather different than those in the Kepler Input Catalog, spectroscopic determination of the stellar parameters are known to be more accurate than the photometric method adopted in the Kepler Input Catalog (e.g.



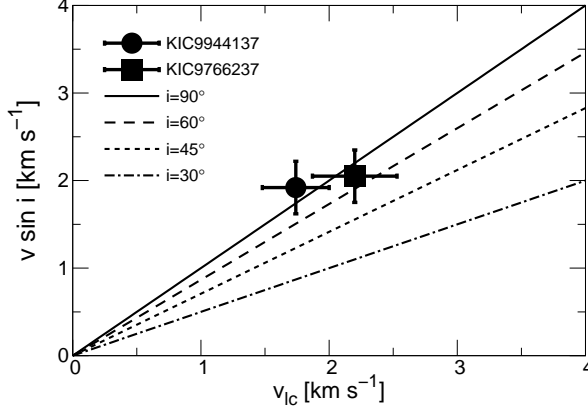
**Fig. 4.** Example of photospheric absorption lines, including Fe I 6213, 6215, 6216, and 6219, of the target stars, and 18 Sco, corrected for the radial velocity. The profiles of these lines are in good agreement of that of 18 Sco, suggesting that both of the targets are single stars. The projected rotational velocity of KIC 9766237, KIC 9944137, and 18 Sco is estimated to be  $2.1(\pm 0.3)$ ,  $1.9(\pm 0.3)$ , and  $2.2(\pm 0.3)$   $\text{km s}^{-1}$ , respectively. The spectrum of KIC 9944137 accompanying that of 18 Sco is shifted by +1.0 along the Y axis, for clarity.

Molenda-Żakowicz et al. 2010; Pinsonneault et al. 2012). Comparison of our 18 Sco data with those in the literature supports the accuracy of our analysis.

The stellar parameters of KIC 9766237, and KIC 9944137 derived here indicate that both stars have the surface gravity and metallicity fairly close to those of the Sun, although the effective temperature of both stars is a little lower ( $\sim 100$  K) than that of the Sun.

The projected rotational velocity of  $2.1(\pm 0.3)$   $\text{km s}^{-1}$  of KIC 9766237, and  $1.9(\pm 0.3)$   $\text{km s}^{-1}$  of KIC 9944137 is consistent with the photometrically estimated rotation period of 21.8, and 25.3 days, respectively, indicating that the inclination angle  $i$  is fairly high,  $i = 90_{-25}^{+0}$  deg for KIC 9766237, and  $i = 75_{-22}^{+15}$  deg for KIC 9944137 (figure 5). The method to derive the rotational velocity on the basis of the light curve was described also by Notsu et al. (2013a), while the data of the isochrone used here was replaced by that in Bressan et al. (2012).

The spectra in the region around 6700 Å are shown in figure 6. The Li I 6708 Å line is detected neither in the spectrum of KIC 9766237 nor in that of KIC 9944137, while it is clearly visible for 18 Sco. The Li abundance  $A(\text{Li})$  is estimated to be smaller than  $A(\text{Li})=1.0$ , on the basis of figure 6. The upper limit of  $A(\text{Li})$  is obtained in another way. Application of the method described in Takeda & Kawanamoto (2005) using the averaged FWHM of weak Fe lines, and signal-to-noise ratio, to our spectra gives the upper limit of the equivalent width of this Li absorption  $\text{EW}(\text{Li})$ ,  $\text{EW}(\text{Li}) < 4.5 \text{ mÅ}$  for both of our targets. The upper limit of



**Fig. 5.** Diagram of the projected rotational velocity vs. rotational velocity estimated from the light curve. The inclination angle is suggested to be fairly high,  $90^{+0}_{-25}$  deg for KIC 9766237, and  $75^{+15}_{-22}$  deg for KIC 9944137. The horizontal error bar is estimated by taking into account the error of the period analysis ( $\sim 10\%$ ), and the error of the radius estimation ( $\sim 10\%$ ), and the vertical error bar is estimated on an assumption that the error is dominated by the error of the estimation of the macroturbulence ( $\sim 15\%$ ; see Hirano et al. 2012).

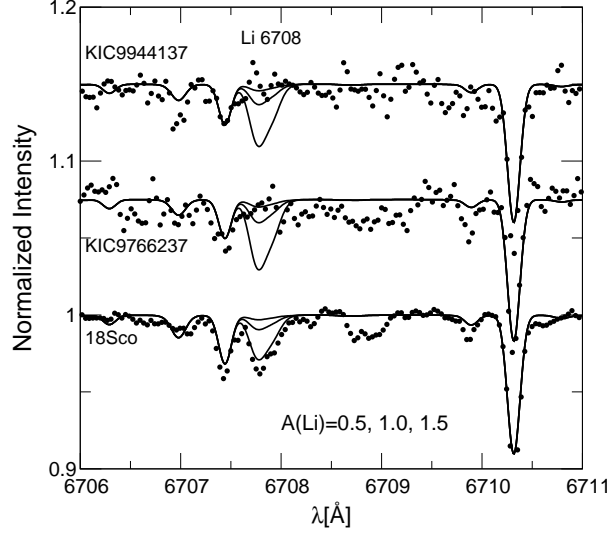
$A(\text{Li})$  is estimated to be  $A(\text{Li}) = 1.37$  for KIC 9766237, and  $A(\text{Li}) = 1.43$  for KIC 9944137, by calculations of the chemical abundances on the assumption of the local thermal equilibrium, atmospheric parameters obtained above, and that upper limit of  $\text{EW}(\text{Li})$ . We here adopt the  $A(\text{Li})$  upper limit of  $A(\text{Li}) = 1.0$ , that is,  $A(\text{Li}) < 1.0$  for our targets. This value is the same as, or less than that of the Sun [ $A(\text{Li})=0.92$ ; Takeda et al. 2010], and is relatively small in the range of the effective temperature around 5700 K (Takeda et al. 2007). This fact suggests that these stars are not young (e.g. Dobrovolskas et al. 2014), and both stars have an age greater than 3-4 Gy, unless an anomalous lithium depletion has occurred. This is consistent with that both stars have a long rotation period, while their activity level seems to be higher than that of the Sun, based on the chromospheric data and on the lower limit for the relative spot areas of about 0.1 %, which is close to the largest sunspots groups observed (0.2 %).

We here briefly discuss whether superflares can be explained by the magnetic energy stored on the surface of KIC 9766237, and KIC 9944137. The average magnetic field of 1-20 G is deduced above, and the total energy of the superflare of our targets is  $10^{34}$  erg. On the assumption that the radiated flare energy is a fraction [ $f$ ;  $f = 0.1$  is assumed in Shibata et al. (2013)] of the magnetic energy stored around the spot area, the flare energy ( $E_{\text{flare}}$ ) is expressed as below (see Shibata et al. 2013):

$$E_{\text{flare}} \sim f \frac{B^2}{8\pi} L^3 \sim f \frac{B^2}{8\pi} (a\pi R_*^2)^{3/2}. \quad (1)$$

In this equation, the length of the magnetic structure responsible for the flare,  $L$ , has been assumed to be equal to the size of the spotted region, i.e.  $L = \sqrt{a * \pi * R_*^2}$ , where  $a$  is the area of the spot in units of the stellar disk area. This equation is transformed by replacing the





**Fig. 6.** Li I 6708 absorption line of KIC 9766237, KIC 9944137, and 18 Sco. The solid lines represent synthetic spectra calculated for the stellar parameters listed in table 1, and different  $A(\text{Li})$  values. The Li I 6708 line basically become shallower with a smaller Li abundance. The  $A(\text{Li})$  value of both targets is estimated to be  $A(\text{Li}) < 1.0$ , although that of 18 Sco is estimated to be  $A(\text{Li}) = 1.6(\pm 0.2)$ , in good agreement with the values in the literature. The spectrum of KIC 9766237, and KIC 9944137 is shifted by +0.075, and +0.15, respectively, along the Y axis, for clarity.

energy with  $10^{34}$  erg, as below:

$$a \sim 0.01 \left( \frac{f}{0.1} \right)^{-\frac{2}{3}} \left( \frac{R_*}{R_\odot} \right)^{-2} \left( \frac{B}{10^3 \text{ G}} \right)^{-\frac{4}{3}}. \quad (2)$$

If the strength of the magnetic field in the spot area is 20 kG, the fraction  $a$  is deduced to be of the order of 0.001 with equation 2. In this case, the average magnetic field results in being  $\sim 20$  G, which is in the range derived above. The 20-kG magnetic field, however, should be too strong, compared to that of the Sun, and physically unrealistic, since the magnetic pressure of the spot area should be up to the same order of the gas pressure in the photosphere. If the strength of the magnetic field in the spot area is 1 kG, the fraction  $a$  is deduced to be of the order of 0.01. In this case, the average magnetic field is of the order of 10 G, which is also in the range derived above. The fraction  $a=0.01$  is, however, an order of magnitude larger than that evaluated from the light curve above. This implies the existence of a large polar spot which are always visible, and does not effectively contribute to the observed variability (see e.g. Hussain et al. 2007). More observations are needed for direct measurement of the spot group area, and the magnetic field strength of the spot group area.

In conclusion, although KIC 9766237, and KIC 9944137 are superflare stars having showed a superflare with an emitted energy of  $10^{34}$  erg, these stars turned out to be a G-type main sequence star with stellar parameters ( $T_{\text{eff}}$ ,  $\log g$ , and  $[\text{Fe}/\text{H}]$ ) close to those of the Sun, by our high dispersion spectroscopy. Their slow rotation period of 21.8 days (KIC 9766237),

and 25.3 days (KIC9944137), and very low lithium abundance of  $A(\text{Li}) < 1.0$  indicate that these stars are not young. The projected rotational velocity derived here is consistent with the photometric rotation period, and these data indicate that the inclination angles are high (70-90 deg). Line profiles of the photospheric absorption lines are in good agreement with those of 18 Sco, suggesting that both of the targets are single stars, though a low-mass companion can not be excluded without additional observations. The average strength of the magnetic field on KIC 9766237, and KIC 9944137 is estimated to be 1-20 G, by the depth of Ca II 8542. These arguments support the hypothesis that the Sun might cause superflares, though the upper limit of this value (20 G) is one order of magnitude larger than that of the Sun. More detailed observations will be needed to clarify the magnetic field on the superflare stars.

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